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Climate Analysis in ʻŌhiʻa Dieback Area on the Island of Hawaiʻi[1]

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ABSTRACT: Studies of climatic fluctuations on the island of Hawaiʻi have been undertaken using data from 113 climatological stations on the windward slopes of Mauna Kea, Mauna Loa, and Kīlauea. Both monthly rainfall and mean monthly air temperature data have been analyzed for periods ranging up to 91 yr. In addition, an estimation scheme for mean monthly air temperatures on the island of Hawaiʻi has been developed. The climate diagram technique of Walter (1971) has been used to relate rainfall and temperature. Annual climate diagrams have been compared to median climate diagrams as an index of periods of relative drought or wetness. Highly significant spatial uniformity in climate fluctuation patterns is found over the study area. The resulting patterns are discussed in relation to observed patterns of ʻōhiʻa (*Metrosideros polymorpha*) dieback in this area of Hawaiʻi.

BEGINNING IN ABOUT 1965, several researchers noted large areas of canopy dieback in the ʻōhiʻa [*Metrosideros polymorpha* Gaud. (Myrtaceae)] forest on the windward slopes of the island of Hawaiʻi (Burgan and Nelson 1972, Mueller-Dombois 1980, Mueller-Dombois and Krajina 1968, Petteys, Burgan, and Nelson 1975). Similar phenomena have been reported in Hawaii since at least 1875 (as cited in USDA, Forest Service 1981). Several disease and insect hypotheses have been considered and discarded as explanations for the decline. Most recent research has focused on the successional hypothesis of Mueller-Dombois (1974: 10), namely that "the ʻōhiʻa dieback is a normal phenomenon, a developmental stage in primary succession of an isolated rain forest ecosystem" (Jacobi 1983, Mueller-Dombois 1980, Mueller-Dombois et al. 1983, USDA, Forest Service 1981).

Mueller-Dombois (1982, also Mueller-Dombois et al. 1983) has recently developed a theory of "cohort senescence" to explain ʻōhiʻa dieback and provide a framework for further research. According to this theory, synchronized tree dieback is a result of a chain reaction involving a predisposing factor (cohort senescence), a precipitating or synchronizing factor (e.g., nutrient stress, storm damage, drought, flooding, etc.), and a hastening factor (e.g., disease or insects).

The present paper reports an analysis of climate fluctuations in the dieback area of the island of Hawaiʻi. Such fluctuations provide a possible precipitating factor for ʻōhiʻa dieback through drought, flooding, or defoliation. Mueller-Dombois (1980: 159–160) speculates that "dieback is initiated by a climatic instability which becomes effective through the soil moisture regime under certain conditions of forest stand maturity." While it is clear that climate fluctuations are not the primary factor in the dieback (Jacobi 1983, Mueller-Dombois 1980, Mueller-Dombois et al. 1983, USDA, Forest Service 1981), they may well provide sufficient stress to cause a stand already weakened by senility or other causes to die synchronously.

In the present work, the author has looked only at patterns of fluctuations of rainfall and temperature through time and their correlations with changes in canopy dieback as seen in the aerial photographs taken in 1954, 1965, 1972, and 1977 (Jacobi 1983, Petteys, Burgan, and Nelson 1975). While recognizing that such correlations are only suggestive, this analysis can increase the plausibility of the hypothesis that stresses due to climate per-

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turbations have played a role in hastening and synchronizing the canopy dieback.

In addition to correlating patterns of climate fluctuations with patterns of canopy dieback, this study has examined the extent to which climate fluctuations are uniform in space over a wide area of the island of Hawai'i; i.e., to what extent geographically separated rainfall and temperature stations, perhaps differing greatly in total rainfall and mean temperature, are nevertheless likely to have less than or greater than the expected (median) rainfall or temperature in the same year. When drought occurs, does it occur across the whole area? And so on.

STUDY AREA

The region of interest to this study is the area analyzed for dieback by aerial photographs, which has been the subject of further studies on the ground by other researchers (Jacobi 1983, Mueller-Dombois 1980, Petteys, Burgan, and Nelson 1975, USDA, Forest Service 1981). This study area consists of about 100,000 ha (approx. 20 × 60 km) of wet forest on the east (windward) slopes of Mauna Kea, Mauna Loa, and Kīlauea (Figure 1). The area extends in altitude from about 500 to 1800 m (1600–6000 ft). *Metrosideros polymorpha*, or 'ōhi'a ('ōhi'a lehua), a native tall tree species, is monodominant in the canopy through most of the study area.

The climate of the area is controlled by four major factors: the northeast tradewinds, which persist approximately 75% of the year; the elevational gradient; the relatively constant day length, due to low latitude; and the buffering effect of the ocean (Blumenstock and Price 1972, Price 1973). The climate is continuously humid, with monthly rainfalls most frequently in excess of 100 mm. Annual rainfall ranges from more than 7500 mm at 1000 m elevation in the middle of the Mauna Kea section of the study area down to about 1800 mm in the south part of the study area on Mauna Loa (DLNR 1970, 1973, Price 1973). In the forest areas above 1200 m elevation, fog interception by the vegetation may substantially increase total effective precipitation (Blumenstock and Price 1972); however, fog drip has not been included in the present study.

Mean annual temperature decreases up the elevational gradient from approximately 25°C (77°F) at sea level to about 10°C (50°F) at 2000 m (6600 ft). There is typically a tradewind inversion layer at 1500–2100 m (5000–7000 ft), above which the temperature lapse rate is less than at lower elevations. This discontinuity in lapse rate occurs near the maximum elevation of the study area. Temperature is equable throughout the year, varying only a few degrees (3–5°C, 5–9°F) summer to winter. Daily temperature ranges exceed the seasonal range in most cases (5–11°C, 8–20°F) (Blumenstock and Price 1972, DLNR 1970, Doty and Mueller-Dombois 1966, Price 1973). The study area fits the category recognized worldwide as tropical montane rain forest (Ellenberg and Mueller-Dombois 1967).

CLIMATE FLUCTUATION INDEX

The present study deals only with monthly rainfall and mean monthly air temperature data. Rainfall data are very abundant for Hawai'i, some stations in the study area going back as far as 1880 with reliable data. Rainfall is highly variable, making occasional droughts or flooding conditions inevitable (Blumenstock and Price 1972). Rainfall data for this project were obtained up to 1975 on computer tape from the project for revision of annual rainfall maps of Hawai'i, Department of Meteorology, University of Hawaii. Later data were obtained from the State of Hawaii, Department of Land and Natural Resources, and from the National Oceanic and Atmospheric Administration (NOAA 1961–1982). Data were used from 113 stations in or near the dieback study area (DLNR 1973), of which 37 with 27–91 yr of data were selected for major analysis (Figure 1). These 37 stations give good coverage of the study area and include data from 1891 to 1982.

Mean monthly air temperature data, on the other hand, are relatively scarce, but temperatures do not vary greatly. Tempera-

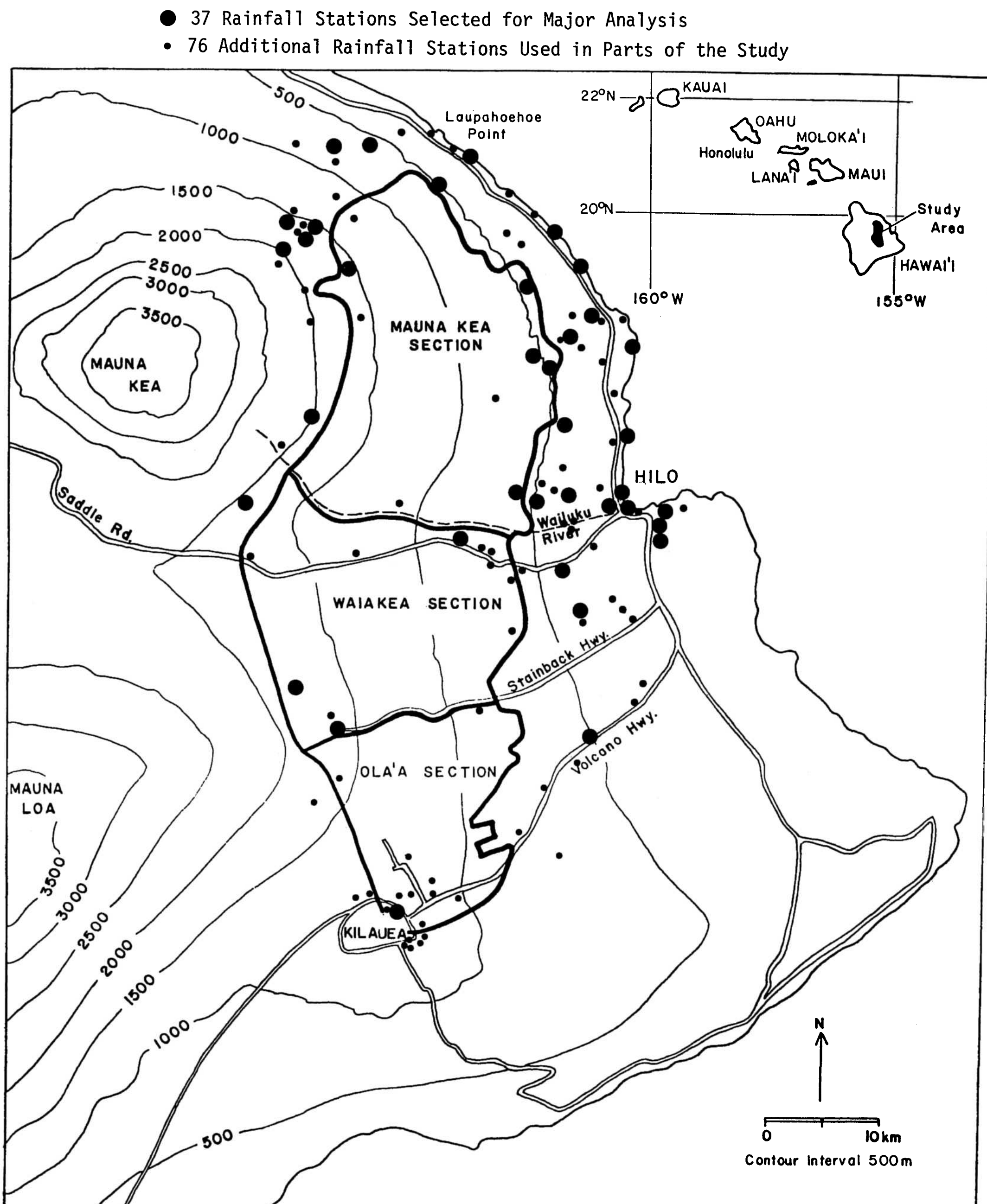

FIGURE 1. Map of the eastern half of the island of Hawai'i, showing the study area and the distribution of the 113 rainfall stations used in the present work. ● = 37 rainfall stations selected for major analysis; • = 76 additional rainfall stations used in parts of the study.

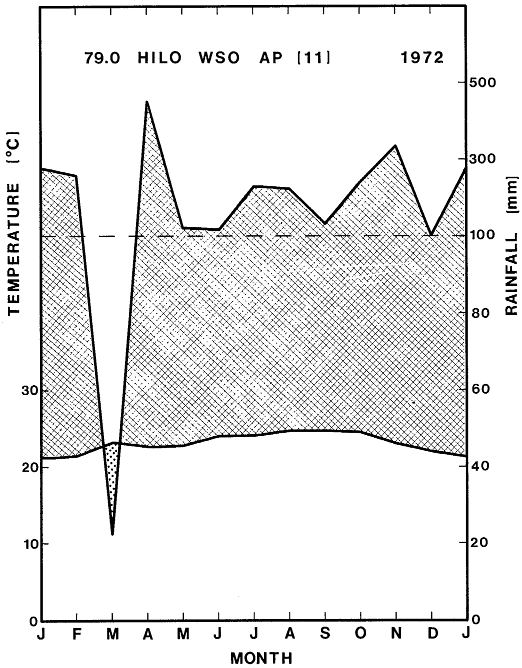

FIGURE 2. Climate diagram for Hilo WSO (Weather Service Office) Airport, 1972.

ture data were obtained from the State of Hawaii, Department of Land and Natural Resources, and from the National Oceanic and Atmospheric Administration (NOAA 1961–1982). Data were used from 36 stations distributed across the entire island (DLNR 1973).

Of the two factors studied, rainfall has the more important effect on the forest as a climate stress factor because of its variability. However, temperature can determine how little rain actually produces drought conditions in the plants. To take crude account of this relationship between rainfall and temperature, these two factors have been combined into climate diagrams as developed by Walter (1971; see also Bridges 1981, Mueller-Dombois 1981*a*) (Figure 2). On these diagrams, mean monthly temperature is plotted on the left-hand ordinate in degrees Celsius and monthly rainfall is plotted in millimeters on the right-hand ordinate. The diagram is scaled so that 10°C corresponds to 20 mm of rainfall. Above 100 mm of rainfall, the scaling is adjusted by a factor of 10 so that each 10°C interval corresponds to 200 mm of rainfall. The scaling is empirically chosen so that water stress is indicated by the precipitation curve falling below the temperature curve. The climate diagram in Figure 2 was chosen to show the two curves crossing; the dotted area indicates a condition of water stress. More direct measurements of potential evapotranspiration have been made on the island of Hawai'i using continuous-level pan evaporimeters. These measures produce an evapotranspiration curve that generally falls slightly above the temperature curve on the climate diagram (Bridges 1981).

In the present study, the area between the rainfall and temperature curves on the climate diagram has been taken as a crude but readily accessible measure of water conditions at a given station for a given year. If the precipitation curve undercuts the temperature curve, that region contributes negative area. (In Figure 2, the total area is measured as the cross-hatched area minus the dotted area.)

A climate fluctuation index is defined to be the climate diagram area minus the median climate diagram area, reflecting relative water conditions compared to the median year. Climate fluctuation indices were calculated for all 113 stations in or near the study area for every year of data. These indices were classed by quartile for each station: the lowest one-fourth of the indices for a given station constitute the first quartile, the next one-fourth make up the second quartile, etc.

AIR TEMPERATURE ESTIMATION

Because of the paucity of air temperature data, a temperature estimation scheme has been developed. Temperature is not highly variable, making errors due to the estimation procedure typically small, and they therefore have little effect on the climate fluctuation index. The quantitatively small but important role played by temperature can be efficiently taken into account by estimated temperatures.

Most of the variation in temperature is due to elevation. Recalling that there is a different temperature lapse rate below and above the inversion layer at about 2000 m (6600 ft) elevation, we omitted data from stations above 2000 m. This left 4322 different values of mean monthly temperature that were used in the estimation procedure.

Analysis of covariance (Bryce 1980) was carried out with the months of the year as levels of a fixed effect and elevation and monthly rainfall as covariates. Initially, latitude and longitude (i.e., location on the island) were also considered as covariates to take typical winds, cloudiness, etc., partially into account. When monthly rainfall was included, the additional explanatory power of latitude and longitude were negligible. Monthly rainfall for each year introduces year-to-year variation in temperature by reflecting some average effect on air temperature of cloudiness, humidity, winds, etc., associated with rainfall. The resulting estimator for temperature T is

$$\begin{aligned} T(\text{in } {}^\circ\text{F}) = 75.1 + 2.47\cos\left(\frac{\pi}{6}M + 0.645\pi\right) \\ - 0.00356(\text{Elevation, in feet}) \\ - 0.52\ln(\text{Monthly rainfall, in inches}) \end{aligned}$$

or

$$\begin{aligned} T(\text{in } {}^\circ\text{C}) = 24.9 + 1.37\cos\left(\frac{\pi}{6}M + 0.645\pi\right) \\ - 0.0065(\text{Elevation, in meters}) \\ - 0.29\ln(\text{Monthly rainfall, in millimeters}) \end{aligned}$$

where M is the month (e.g., in January, $M = 1$; in February, $M = 2$; etc.). The natural logarithm (ln) of the monthly rainfall has been used instead of the rainfall itself. The reason for this is that rainfall is an ill-behaved variable; its standard deviation is correlated with its mean. This correlation is removed by the logarithmic transformation, giving very nice, evenly scattered residuals to the fit.

These factors explain 94.4% (R^2) of the variance in the 4322 temperature points, leaving a standard deviation of 1.48°F (0.82°C). The fit is very highly significant ($p < 0.0001$). It applies over the whole island below 2000 m (6600 ft).

This estimate for temperature shows weak, but definite, seasonality through the cosine term. It is maximum on about 20 August and minimum on about 18 February for equal amounts of rainfall. The first two terms of this function are the same as the function discussed in more detail by Bridges (1981). This function comes very close to the fit done by Bridges of the mean monthly air temperature at Hawaii Volcanoes National Park Headquarters. When appropriate elevation and rainfall data are inserted, maxima and minima are at about the same dates, and the mean temperature and annual amplitude are within a few tenths of a degree of those Bridges obtained by direct fit to that station alone.

As an example of the use of this estimate, consider Hilo WSO Airport, elevation 36 ft, for May 1981 ($M = 5$). The rainfall for that month was 4.16 in. (5.91 in. below normal). Then we estimate

$$\begin{aligned} T &= 75.1 + 2.47\cos\left(\frac{5\pi}{6} + 0.645\pi\right) \\ &\quad - 0.00356(36) - 0.520\ln(4.16) \\ &= 74.1^\circ\text{F} \end{aligned}$$

The mean temperature actually recorded for May 1981 was 74.2°F (0.7°F above normal) (data from NOAA 1961–1982).

INDEX OF UNIFORMITY AND CORRELATION

To evaluate the pattern shown by climate fluctuation indices calculated for so many stations (113), it was necessary to study the uniformity of pattern across the study area. Do we have to look at localized patterns, or is there sufficient uniformity to allow an aggregate pattern to be considered? Using information theory, in analogy to Colwell's (1974) indices of predictability, constancy, and contingency for periodic phenomena, three indices for stations distributed non-uniformly in space have been defined (Evenson 1985). The three indices are uniformity, persistence, and contingency. All three range from zero to one. Uniformity (U) measures the extent to which all stations tend to show the same pattern. Persistence (P) measures the extent to which U is due to a single pattern that persists year after year. Contingency (C) measures the extent to which U is due to patterns that change from year to year, still maintaining similarity for all stations in a given year. The three indices are related so that

$$U = P + C$$

A chi-squared test statistic is associated with each index.

For the 37 major stations, Pearson's correlation coefficient was calculated between all overlapping runs of (logarithmically transformed) rainfall data (Ryan, Joiner, and Ryan 1976).

RESULTS AND DISCUSSION

Uniformity (U) of quartile ranking was calculated by taking all data since 1880, 113 stations, calculating climate fluctuation indices for each station in each year, then placing each year's index in the appropriate quartile for that station. Requiring a minimum of 10 yr of data for any station to be included in the calculation, the result was $U = 0.41$, 99.99% of which was contingency, 0.01% persistence. Persistence P is not statistically different from 0, but U is very highly significantly different from 0 ($p < 0.0001$). So there is very significant uniformity of climate pattern across the area in a given year.

This result is as expected: significant uniformity, negligible persistence, but significant contingency. The most obvious characteristic of rainfall data is its variability. Mild familiarity with such data leads to the expectation of low persistence, since persistence implies that the climate fluctuation index at any given station tends typically to remain in the same quartile for many years in a run. Hence, if there is to be any appreciable uniformity, it must be through contingency, i.e., a continually changing pattern with most stations changing together from year to year.

Establishing significant uniformity of climate fluctuation patterns could greatly aid future attempts to include climate as a factor in ecological studies in Hawai'i. If the result generalizes to other high islands, it could be equally important elsewhere in the Pacific. While it is not a particularly surprising result, it has not been previously demonstrated from the data in Hawai'i, and most scientists have been reluctant to make this assumption, because the uniformity in space is not readily apparent in raw data but only in differences from the median. Furthermore, the uniformity is far from absolute and must be interpreted and used with care. The present result indicates that just under half the information about spatial variation of climate over a long period of time is contained in the assumption of uniformity.

In calculations of Pearson's correlation coefficient between overlapping runs of (logarithmically transformed) rainfall data for the 37 major stations, the median correlation was about 0.8. Seventy-six percent of the correlations between stations were greater than 0.7. So the correlation coefficients lead to the same conclusion as the uniformity index, by indicating that rainfall amounts at stations across the whole study area are highly correlated, i.e., they change together over the years.

Given the significant uniformity of the climate fluctuation patterns in the study area, it is reasonable to look at those patterns on an aggregate basis. The mean quartile number (according to climate fluctuation indices) for all stations in a given year is shown in Figure 3 from 1940 to 1981. If the stations are distributed randomly among the four quartiles in a given year, then the mean quartile number will be 2.5, as shown by the horizontal line. Of particular interest to this study are periods of unusual drought or wetness, such as the 1971–1978 dry period (most stations in the lower quartiles). Substantially the same pattern is shown by mean annual rainfall, averaged over all stations in the study area for each year (Figure 4).

Petteys, Burgan, and Nelson (1975) and Jacobi (1983) have carried out analyses of the aerial photographs taken in 1954, 1965, 1972, and 1977 to document the progress of the dieback. Petteys, Burgan, and Nelson

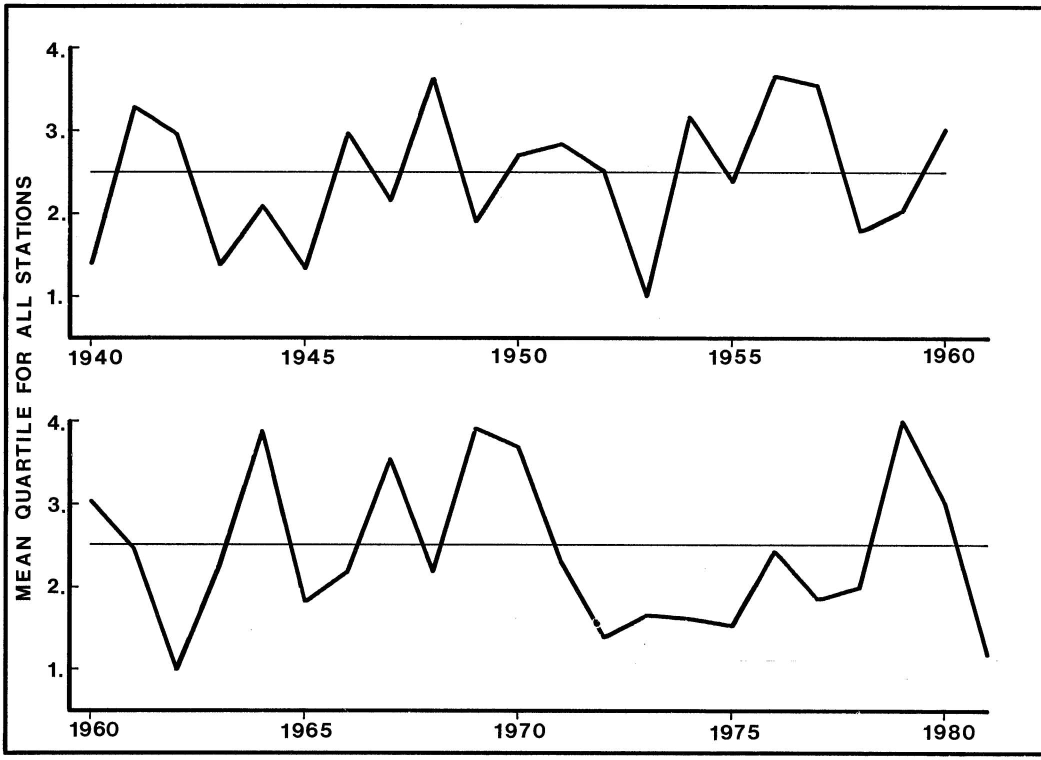

FIGURE 3. Mean quartile number for 113 stations in dieback area, 1940–1981.

studied an area of 79,800 ha (197,300 acres), largely overlapping the area of the present research. They found the forest to be 42% healthy and 0.2% in severe decline in 1954. In 1965, however, it was only 26% healthy and 22% in severe decline. By 1972, they found only 18% healthy forest and 48% in severe decline. On the basis of this startling increase, they referred to the decline as an "epidemic" and expressed fear of "virtual elimination of the ohia forest ... within 15 to 25 years if the present rate of damage continues" (Petteys, Burgan, and Nelson 1975:1; see also 3 and 10–11).

Jacobi (1983) used aerial photographs to evaluate an area of 1600 ha (3950 acres) near Saddle Road. He found the entire site to be healthy in 1954. By 1965, 28% of the forest showed significant canopy decline. By 1977, the canopy decline had increased to 63%. In addition to the evidence from the aerial photographs, his own field work (Jacobi 1983:86) indicates that "the pattern of distribution of dieback seen on the 1977 photographs is essentially identical to its distribution in 1981." Along the transect in his study, 71% of the trees were unhealthy. Jacobi (1983:86) also cites discussions with local residents who have hunted in the dieback area, indicating that the "dieback first became noticeable in the early 1960s, and had reached its greatest extent by 1974."

The most that the climate fluctuation patterns can tell us at this stage of the research is that there are indeed large fluctuations in relative water availability, compared to the median year. Such fluctuations could produce either flooding or drought conditions across essentially the whole dieback area, depending on different soil conditions. Mueller-Dombois (1981*b*) has recognized five different dieback types associated with different soil and moisture regimes and proceeding at different rates. If the dieback of the early

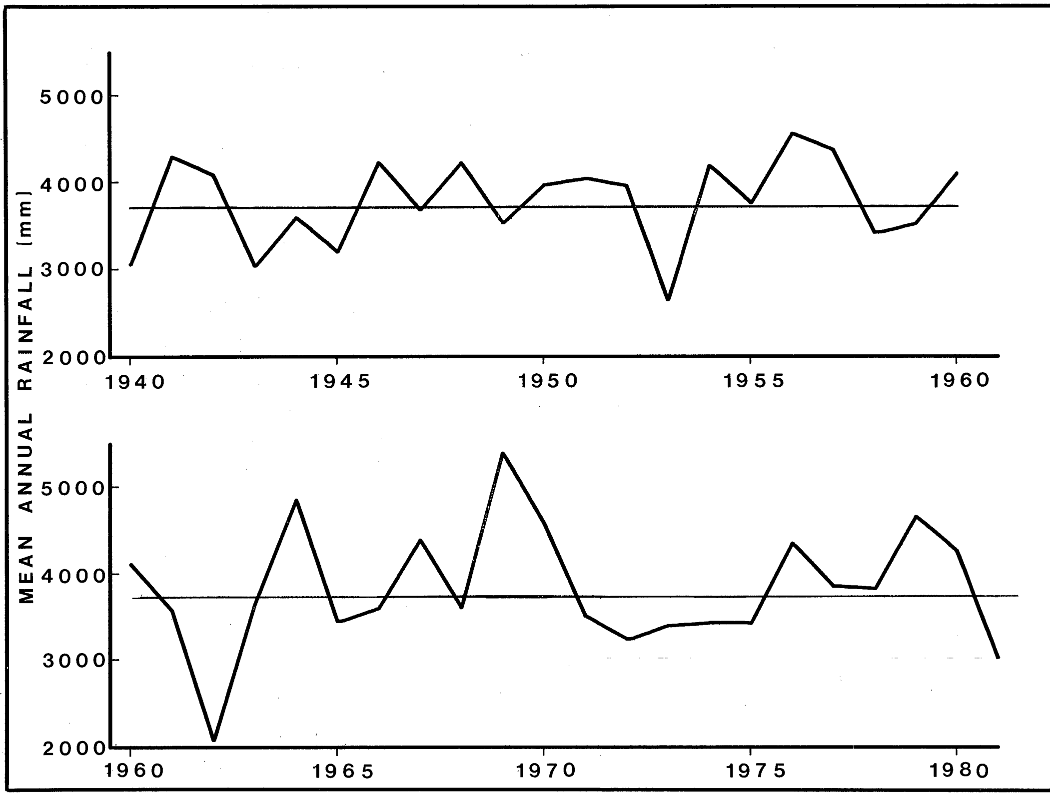

FIGURE 4. Mean annual rainfall for 113 stations in dieback area, 1940–1981. Horizontal line shows median value of mean annual rainfalls for the whole period.

1960s was synchronized by climate perturbations, then it is possible that the unusually wet years of the middle-to-late 1950s contributed to wetland dieback, and perhaps the dry years of 1958–1959 and 1962 contributed to dryland dieback. Similarly, the wet years, 1969 and 1970, could have contributed to the sharp increase in canopy decline between the 1965 and 1972 or 1977 aerial photographs. The different rates of dieback for the different types suggest different lag times for effects of climate perturbations to be noticed. Thus, it is not clear at this point which of the fluctuations to associate with particular dieback events.

If a forest stand represents a cohort that is in weakened condition due to senescence, then relatively short periods of flooding or drought (perhaps appreciably less than the 1 yr resolution time of the present study) could "trigger" canopy decline. The appropriate time scale for relating climate fluctuations to decline depends on soil buffering as well as on stand condition. Varying the time scale of the climate fluctuation index from 1 yr, as used exclusively in the present research, may help clarify these effects, especially if stream runoff and groundwater data are also considered (Doty 1981).

Other effects that need to be taken into account in future work include storms, using both stream runoff data and wind data, and a more accurate index of water stress in the trees.

The present research concludes that climate stress could play a precipitating and synchronizing role in canopy dieback, but much more information is necessary to take that proposition out of the speculative realm. More definitely, we can conclude that climate fluctuations have considerable uniformity over the whole dieback area, and that aggregate examination of fluctuation patterns will often be sufficient over this area.

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